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Adiabatic Compression of Pores in Mixed Fuel Medium During Launching*

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Abstract: The charge of fuel air explosive (FAE) warhead is usually a solid-liquid mixed fuel, which contains pores to meet the usage and reservation. This study has investigated the influence of pore size on the launching safety by analyzing the physical process of the pore compressing. A criterion is proposed to distinguish the influence of pore size on charge safety in launching, and a quantitative relationship of the launching acceleration, the size of the pore and the temperature of pore in adiabatic compression has been established.

Key words: fuel air explosive; mixed fuel; adiabatic compression; warhead

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1 Introduction

Fuel air explosive (FAE) weapon has strong explosion power and obvious damage superiority, so it has been followed with universal interest in many countries. The high FAE fuel usually is solid-liquid mixed. The mixed fuel must meet not only the demand of the detonative power but also the demand of weapon properties in use and reserve. One of the properties is to ensure the physical stability of the solid-liquid mixed fuel charged in the warhead case of weapon in the process of use and reserve. The solid component in the mixed fuel is aluminum powder. There must be pores in the mixed fuel to meet the need of physical stability of the mixed fuel. The pore size may not exceed that of the aluminum powder grain. The pores may be compressed quickly, which can make the temperature heightened. Therefore the pores in mixed fuel have an important influence on the fuel's safety in process of launching warhead.

The former about the charged explosive launching safety studies concentrates primarily in the solid explosive[1~25]. The solid-liquid mixed fuel is quite different from the solid explosive in the physical and mechanical properties, so the law about the influence of flaws in the mixed fuel medium on launching safety can not be explained by the corresponding conclusions of the solid explosive. The literatures on the investigation of this aspect have not been available now.

2 The Pores' Adiabatic Compression Caused by the Acceleration of Launching

In process of warhead launching, the propellants push the bottom of the warhead and produce shock effect to the mixed fuel in the warhead case. The stress wave is produced at the bottom of the

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warhead, it transmits from the bottom to the top in the fuel medium in the warhead case. Under the action of the stress wave, the pores in fuel medium are compressed. When the pores are compressed, heat will be produced. The temperature of the medium in the pores is heightened, the transmission of the stress wave is so instantaneous that the transmission of the heat produced can be ignored. Therefore the process of the pores being compressed can be considered as an adiabatic process.

The pores in solid-liquid mixed fuel contain both the volatile gas of liquid ingredient and air. When it is considered as polytropic gases, its specific heat capacity c_v is a constant. The conservation equation of the inner energy is

$$\frac{\mathrm{d}e}{\mathrm{d}t} + p\frac{\mathrm{d}v}{\mathrm{d}t} = \frac{\mathrm{d}Q}{\mathrm{d}t} \tag{1}$$

In the equation, e is the inner energy, p the pressure, v the capacity, Q the heat quantity, t the time. For an adiabatic problem, there is $\mathrm{d}Q/\mathrm{d}t=0$, then Eq. (1) becomes

$$\frac{\mathrm{d}e}{\mathrm{d}t} = -p\frac{\mathrm{d}v}{\mathrm{d}t} \tag{2}$$

The state equation of polytropic gases is

$$pv^{\gamma} = A \tag{3}$$

Where γ is polytropic index, A is a constant

$$A = p_0 v_0^{\gamma} \tag{4}$$

Where p_0 is the initial pressure, v_0 is the initial specific capacity of the medium in the pores. For polytropic gases, obtain from Eq. (2)

$$c_v T = pv/(\gamma - 1) \tag{5}$$

Where T is the instantaneous temperature of the compressed medium in the pores. The pores in the mixed fuel contain the air and the vaporized gas from liquid components. The gas vaporization has something to do with temperature. The heat capacity of the vaporized gas will be obtained throng the experiments, which is to be done in the future. That the bore contains only air is considered approximately in the paper. Supposing the medium in the pores in the mixed fuel is air, c_v the heat capacity of the air, which changes corresponding to the temperature[26]. For $T=100\sim2\,500$ K, there is $c_v=(0.74\sim1.21)$ kJ/(kg · K); approximately analyzing, take $c_v=1$ kJ/(kg · K). For air, $p_0=0.1$ MPa, $\rho_0=1.25$ kg/m^3, $\gamma=1.4$. The temperature of themedium in the pores under different pressures is available from Eqs. (3)～(5). If the pressure in the pores $p=200$ MPa, then $T=1\,754$ K. For the mixed fuel ingredients so high temperature obviously is dangerous, which may cause the charged fuel explosion. Similarly, Table 1 can be obtained.

Table 1 The temperature of the medium in the pores under different pressure

p/(MPa)	T/(K)	p/(MPa)	T/(K)
2	470	100	1439
4	573	200	1754
20	908	400	2139

According to the definition of the inner energy, there is

$$\mathrm{d}e = \left(\frac{\partial e}{\partial T}\right)_v \mathrm{d}T + \left(\frac{\partial e}{\partial v}\right)_T \mathrm{d}v = -p\mathrm{d}v$$

For the incompressible medium, $\mathrm{d}v=0$, the above equation becomes

$$\mathrm{d}e = \left(\frac{\partial e}{\partial T}\right)_v \mathrm{d}T = 0$$

The inner energy changes corresponding to the temperature, namely $(\partial e/\partial T)_v \neq 0$ so $\mathrm{d}T=0$. That is to say, for the incompressible medium overloading pressure can't heighten the temperature. So if pores in the charge are inexistent, the high temperature will not be produced owing to the adiabatic compression in launching process of warhead. The launching will be safe under this condition.

3 Overloading Stress and the Rate of the Stress

In the launching process, the warhead is pushed from its back by the pressure in the bore, the stress wave transmits from the bottom to the top. The load strength in the bottom charge in the warhead case is maxim, which should be key for launching safety of the charged explosive. On the stress wave front in the fuel medium in the warhead case, the stress augments along with the time, which can be expressed by $(\mathrm{d}\sigma/\mathrm{d}t)$. The stress at some point in the fuel medium in the warhead case will change along with the time (Fig. 2). If the size of the pores in the fuel medium in the warhead case is small enough, under the less stress action, pores can be closed. In this process the stress starts from zero to the some value. The adiabatic compression in the pores can't bring high temperature, according as the equation of conversation of momentum. For the stress wave front in the fuel medium, there is

$$\mathrm{d}\sigma_{\mathrm{f}}=\rho_{\mathrm{f}}c_{\mathrm{f}}\mathrm{d}v_{\mathrm{f}} \tag{6}$$

Where σ_{f} is the instantaneous stress of the stress wave front, v_{f} the particle velocity of the stress wave front, ρ_{f} the initial density of the mixed fuel medium; c_{f} the longitudinal wave velocity of the fuel medium. Eq. (6) may be integrated as

$$\sigma_{\mathrm{f}}=\rho_{\mathrm{f}}c_{\mathrm{f}}v_{\mathrm{f}} \tag{7}$$

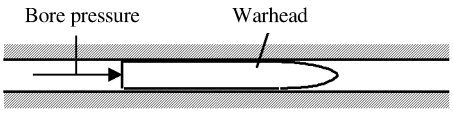


Fig. 1　The launching process of the warhead

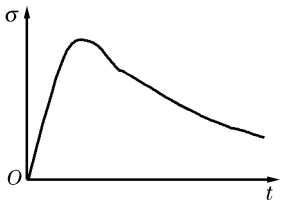


Fig. 2　The stress wave of the filling medium in the warhead

Under the action of the stress wave, the pores in the mixed fuel medium shrink gradually, and the pressure in the pore heightens by degrees. When the pressure in the pore is equal to that on the local stress wave front, the pore stop shrinking.

As the stress wave transmits in the fuel medium, it will be reflected on the interface between solid-liquid fuel and gas which is the pore boundary. The pressure in the pores is enlarged by degrees when they are compressed. Its minimum is the initial pressure. The gas has good condensability, so before the pore shuts the pressure in the pore attains maximum. The maximum is the local stress wave's pressure. The initial pressure is minimum. The pore's boundary is corresponding to a free surface. The velocity of the free surface is double the particle velocity of the incidence stress wave. Before the pores are closed, the pressure is maximal, At this time, the boundary will disappear, and the particle velocity is equal to the local particle velocity on stress wave front. Therefore in process of pores being closed the shift velocity of the pore's boundary changes as the following equation described

$$v_{\mathrm{e}}=(1\sim 2)v_{\mathrm{f}} \tag{8}$$

Where v_{e} is the shift velocity of pore's boundary under the action of the stress wave. Suppose the size of the pores in the fuel medium in the warhead case is l, then the time needed by closing the pores are determined by the following equation

$$\frac{\mathrm{d}l}{\mathrm{d}t}=(1\sim 2)v_{\mathrm{f}} \tag{9}$$

Approximately analyzing, take

$$\frac{dl}{dt}=1.5v_f$$

The magnitude of the stress wave in the fuel medium of the warhead is related to the overloading process, the particle acceleration of the interface between the fuel and the warhead case bottom is launching acceleration on the stage of stress wave overloading

$$\frac{dv_f(t,x_0)}{dt}=a \tag{10}$$

Where a is the warhead launching acceleration which is a constant approximately. t can be calculated out through the upper Eqs. (9) and (10)

$$t=\sqrt{2l/1.5a} \tag{11}$$

In general, the axial size of the warhead is much bigger than the radial size, so that the stress wave formed during the launching process can be considered as one-dimensional. Therefore, there is

$$\dot{\sigma}_f=\rho_f c_f \dot{v}_f \tag{12}$$

Where $\dot{\sigma}_f=d\sigma_f/dt$. At the bottom of the warhead case, there is

$$\dot{\sigma}_f=\rho_f c_f a \tag{13}$$

The acceleration a approximately is a constant during the launching process, and σ_f is also a constant which can be seen from Eq. (13), therefore

$$\sigma=\dot{\sigma}_f t \tag{14}$$

When the pore is closed, σ_e can be calculated out through Eqs. (11) and (14).

$$\sigma_e=\rho_f c_f\sqrt{2la/1.5} \tag{15}$$

The bigger the acceleration, the bigger the pressure in the compressed pore and the bigger the pore size, the bigger the pressure in the compressed pore. The bigger pressure in the compressed pore, will form the higher temperature during the compressed process, rising the problem of launching security. It is more disadvantageous to launch in the safety, which can be known from Eq. (15). The pore size is related to the charge technology and the mixed fuel components. The pore size is decided by the solid grain size of the fuel components which cannot be bigger than the maximal size of the solid grain under the condition of a good charge technology.

4 The Determinant of the Pore Size Engendering Explosion

Suppose $\rho_f=1\,430$ kg/m^3, $c_f=300$ m/s, $a=100$ km/s^2, $l=70$ μm, and we can get that $\sigma_e=4$ MPa from Eq. (15). The corresponding temperature produced by adiabatic compress of the pores is 573 K, which can be acquired from Table 1. There may be accidents of exploding ahead of schedule in launching of warhead if the spontaneous combustion temperature of the mixed fuel components is lower than 573 K.

Using the test system described as Fig. (3) to test the critical detonation temperature of the mixed FAE fuel and getting the value of the critical detonation temperature is 483 K, according to the value of the critical detonation temperature and the heightened value of the temperature coming from the pores' adiabatic compression, the fuel launching safety can be forecasted.

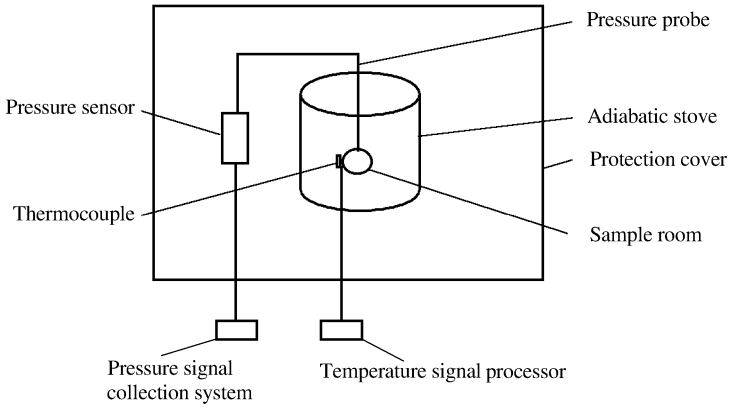


Fig. 3　The device for checking critical detonation temperature of the fuel

5　The Problem on Designing Parameters of the Launching Simulation Devices

For the sake of checking the warhead charge launching safety, launching experiment is done by the simulation device which is beneficial to the safety and reduce the cost of the experiment. It is difficult for the simulation device to simulate to the practical launching device in the aspects of size and physics process completely.

The aim of the simulation device is to examine the charge launching safety, so the simulation device should have pertinent parameters to keep the checking effectiveness on the charge launching safety.

The charge launching safety primarily lies on the charge mass and the charge physical flaws (cracks, pores) which have vital influence on the launching safety. The charge physical flaws parameters of the launching process should be paid particular attention while designing the launching simulation device.

The parameters that influence the charge launching safety are acceleration, the propellant pressure in the chamber and the time of the overloading. The stress in the bottom of charge in the warhead case will be caused by the overloading acceleration. The propellant pressure in the chamber influences not only on the overloading acceleration but also on the magnitude of the stress wave in the mixed fuel of the warhead under the condition of a given warhead mass. The influence of the overloading time on the charge launching safety has been realized, but there has been no quantitative research available until now.

There can't be cracks in the filling process because the fuel is solid-liquid mixed, so the pores is the sole flaw for the mixed fuel charge. From that we know the launching overloading simulation devices should satisfy for the minimal overloading time that can be acquired from the Eq. (11). The minimal overloading time is decided by the size of the charge pores and the overloading acceleration.

Suppose $l = 70\ \mu\text{m}$, $a = 100\ \text{km/s}^2$, the minimal overloading time can be calculated out from Eq. (11): $t = 2.3\ \mu\text{s}$. In order to keep the feasibility of the simulation device checking the warhead charge safety the simulation device overloading acceleration time should not be less than $2.3\ \mu\text{s}$, which is easily to be satisfied.

6 Conclusions

The pore size of the mixed fuel medium in the warhead case plays an important role on the charge launching safety. The FAE weapon is usually filled by solid-liquid mixed fuel, which has big different from the traditional solid explosives on the physical and mechanical properties. The pores' size and their distributing state are completely different from the traditional solid explosives either. Therefore, the theories calculating mechanical action of the launching process for the mixed fuel can not be substituted by that of the traditional solid explosive. The determinant rules of explosion ahead of schedule have been founded through analyzing pores compressing physical process among the mixed fuel in this paper. The theoretical foundation for the designing of the FAE fuel components and the methods for determining the FAE weapons' launching safety are also provided in this study.

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发射过程中混合燃料介质内孔隙的绝热压缩

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摘要:燃料空气炸药武器战斗部装填的云爆剂一般是固液混合态,固液混合药剂介质内部难免存在孔隙,孔隙尺度对发射安全性有重要影响。通过对孔隙压缩物理过程的理论分析,研究孔隙尺度对混合燃料发射安全性的影响,建立了相应的判别准则,给出发射过载加速度、混合燃料介质内孔隙尺度、孔隙绝热压缩温度之间的定量关系,并提出了发射模拟装置设计应考虑战斗部内装药缺陷的有关参数,给出相应的设计依据。固液混合燃料介质内孔隙的尺度越小,其压缩产生的温度越低,抗过载能力就越强。如果圆形孔隙的直径为70 μm,在发射过载加速度为100 km/s^{2}的情况下,孔隙压缩产生的最高温度约573 K。将该值与固液混合药剂能够承受的临界温度进行比较,就可判断药剂在发射过载过程中的安全性。

关键词:燃料空气炸药;发射安全性;绝热压缩;战斗部

中图分类号:O389;TQ564.4 **文献标识码**:A

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